

HIGHLY-EVOLVED STARS

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1. INTRODUCTION

According to current theories of stellar evolution, any star will eventually exhaust all its sources of energy, and become some kind of compact object--a degenerate dwarf, neutron star, or black hole. A low-mass red giant slowly loses its outer envelope, while its core continues to contract, and it ultimately becomes a degenerate dwarf. A higher-mass red giant undergoes a supernova event, in which the core collapses while the outer layers explode. For a star of intermediate mass, the explosion is powerful enough to drive off the envelope, and the core becomes a neutron star. For a massive star, however, the explosion is not strong enough to eject the whole envelope, and the star as a whole collapses further to form a black hole.

These three end-products of stellar evolution--the degenerate dwarf, neutron star, and black hole--and their immediate precursors manifest themselves in the optical region of the spectrum in a wide variety of species (Table 1), which I've classified according to whether they are isolated stars (i.e. single or non-interacting), components of close interacting binaries, or members of a globular cluster.

Table I
Optical Appearance of Highly-Evolved Stars

	O b s e r v a b l e S p e c i e s		
	Isolated	Interacting Binary	Globular Cluster
Compact Object			
Black Hole		X-Ray Binary	?
Neutron Star	Pulsar ↑ SN	X-Ray Binary	?
Degenerate Dwarf	White Dwarf ↑ Planetary Sub-dwarf	Cataclysmic Variable AM Her Object Sco X-1 Like Object	

Isolated Stars

While isolated black holes, by definition, are unobservable, isolated neutron stars reveal themselves as pulsars, and isolated degenerate stars are visible as white dwarfs. Their immediate precursors are believed to be the central stars of planetary nebulae and other hot "sub-dwarfs".

Interacting Binaries

The compact objects manifest themselves most spectacularly, if indirectly, as components of close, interacting binaries. Although the compact component is usually invisible, it makes its presence unmistakably clear in accreting material supplied by a nearby "normal" companion, which for one reason or another (stellar wind, rotational ejection, Roche-lobe overflow) is losing mass. In the process of infall to the compact object, gravitational energy is released, some of which goes into radiation. It is not surprising, then, that all these classes of interacting binaries involving compact objects have among them at least some objects which are known to be X-ray sources. Cyg X-1 is, perhaps, the most promising black-hole candidate. So far, there are at least 14 binaries having neutron-star companions known. There are several types of binaries containing degenerate dwarfs of which I have listed only a few. One type is the cataclysmic variables (novae, dwarf novae and recurrent novae) in which the compact companion is a non-magnetic or weakly magnetic degenerate dwarf. Another type, of which AM Her is the most spectacular example, is the binaries which contain a highly magnetic degenerate dwarf.

Globular Clusters

We may consider globular clusters as a class of "highly evolved" stars not only because they contain stars which have exhausted or are close to exhausting their nuclear fuels but also because they are highly evolved dynamically, with relaxation leading to very dense central regions. It is now known that globular clusters are a class of objects in which x-ray emission is two orders of magnitude more probable than for the galaxy as a whole (ref. 1). Why this should be so is unclear, but this finding has led to suggestions of massive black-holes accreting stellar debris (ref. 2) and formation of binaries by capture of field stars (ref. 1) in the dense central regions.

All these objects are of great interest, not only because they define the end-points of stellar evolution, but also because they represent extreme physical conditions not accessible in a terrestrial laboratory. As a rule, however, these objects are faint optically, either due to low intrinsic luminosity or interstellar extinction, and until 1978 they were observed in the ultraviolet only with medium or wide-band filters, if at all. The IUE, however, has made it possible to obtain ultraviolet spectra of these objects, sometimes even at high dispersion. The most promising black hole candidate, Cyg X-1, has been observed by IUE with full phase coverage. The IUE has also observed the Crab pulsar; and I believe that Benvenuti will be reporting the results later in this symposium. The IUE has been used to obtain ultraviolet phase coverage of six x-ray binaries believed to contain neutron-star companions, and it has observed dozens of degenerate and pre-degenerate stars.

Because studies of highly evolved stars with the IUE have been so extensive, this review can only describe a few selected topics. The appendix to this review, however, contains a list of published observations up until the time of this review.

2. PRE-DEGENERATE HOT STARS

Elemental Abundances

Beyond the statement that subluminoous, blue stars are highly-evolved solar-mass stars in the process of becoming white dwarfs, the evolutionary status of these stars is not well understood; nor is it understood even to what extent these objects form a homogeneous group. Part of the problem is that their physical parameters, particularly surface chemical compositions, have not been determined. Analyses of IUE spectra, which contain strong lines of important elements such as He, C, N and Si, however, are now proving useful in defining the parameters for these stars. The lion's share of the work has been carried by the Kiel astronomers (ref. 3-6), who have performed non-LTE analyses of IUE spectra of hot sub-dwarfs. Their results for three sdO stars are shown in Table II. Note that in all three stars, helium is enriched, the carbon-to-nitrogen abundance ratio is very low, but the silicon abundance is normal. As the Kiel group points out, the normal abundance of silicon, which should well represent the "metals", rules out gravitational settling of heavy elements. However, the overabundance of nitrogen and helium and the depletion of carbon indicate prior processing by the CNO-cycle.

Table II

Compositions of 3 sdO Stars
(from Gruschinske, Hunger, Kudritzki, Simon,
Kiel University [ref. 3-6])

	Abundances Relative to Sun			
	He	C	N	Si
HD 49798	2.8	0.4	25	1.4
HD 127493	3.0	0.02	8	1.4
BD +75°325	3.0	0.4	12	1.1

Stellar Winds

One of the first discoveries made with the IUE (ref. 7) was that the UV spectra of some hot, subluminoous stars have P Cygni lines, indicating high-velocity mass-loss very much like that inferred in young OB stars. Subsequent analyses of the profiles of these lines, as obtained from high-dispersion IUE spectra, have confirmed the detailed similarities of winds in these two groups of stars, which are at opposite extremes of stellar evolution. It is

now clear that these hot, subluminous stars serve as an excellent laboratory for studying the properties of high-velocity winds, because they provide a broad range of stellar parameters, like effective temperature or escape velocity, to correlate with wind characteristics. Figure 1 shows a temperature-gravity plot of some subluminous O stars which have been observed by IUE. Note that most of these stars undergoing high-velocity mass loss fall in a well-defined region bounded by particular L/\dot{M} ratios. These boundaries are the same as those for young massive O stars (cf. ref. 8). Also as with young O stars, there is a general trend of increasing terminal velocity of the wind with stellar escape velocity. These similarities suggest that mass-loss in hot stars is an atmospheric phenomenon, totally unrelated to interior structure, which of course must be very different for young OB stars and these old, subluminous stars. The correlation of the presence of the wind with L/\dot{M} and the correlation of terminal to escape velocity are consistent with radiation-driven mass loss (cf. ref. 9).

There is one outstanding exception to the empirical criterion above for the presence of a wind. This exception is the central star of NGC 2392, whose visual spectrum indicates an O6f spectral type but whose ultraviolet spectrum is continuous. I have been pondering this fact for two years now and still have no good explanation.

The wind of one particular star, the nucleus of NG 6543, has been studied intensively. The spectral type of the central star is midway between Of and WR. Analysis of high-dispersion profiles of the wind lines (shown in Figure 2) indicates a rate of mass loss, $\dot{M} \approx 7 \times 10^{-7} M_{\odot}/\text{yr.}$, which exceeds the theoretical maximum mass-loss rate given by radiation-driven winds. Analysis of the profiles as obtained from low-dispersion spectra via a clever technique devised by Castor, Lutz and Seaton (ref. 10) yields similar results for this central star. I mention this technique, since it was developed specifically for IUE low-dispersion spectra, and should prove exceedingly useful for studying winds in stars too faint for high-dispersion spectroscopy.

3. DEGENERATE STARS

X-Ray Emission in White Dwarfs

About five years ago, it was discovered (ref. 1) that Sirius B, the white-dwarf component of Sirius, is a soft x-ray source. One explanation (ref. 12, 13) was that soft x-ray radiation produced in the deep photosphere could escape from a metal-deficient atmosphere and would yield the observed fluxes, provided that the effective temperature exceeds 32000°K. Another explanation was that coronal emission from an envelope surrounding Sirius A or Sirius B provides the observed x-rays. These possibilities are ruled out by Böhm-Vitense et al.'s (ref. 14) IUE observations which show that (1) the UV absolute flux distribution yields an effective temperature of only 26,000°K which is too low for the production of soft x-rays, and (2) no emission lines indicative of a chromosphere or corona are present in the UV spectrum of either Sirius A or Sirius B, at least at low dispersion. Escape of deep photospheric emission does appear to be valid, however, for another hot white dwarf, HZ 43, which is the brightest ultra-soft-x-ray source in the sky. Oke and

Greenstein's (ref. 13) IUE observations showed that its $T_{\text{eff}} \approx 60000^\circ\text{K}$, making it one of the hottest white dwarfs known.

The Nature of Cataclysmic Variables (Novae, Recurrent Novae, Dwarf Novae)

It is generally believed that cataclysmic variables are close binaries in which the red component fills its Roche-lobe and transfers matter, via an accretion disk, onto a white dwarf (ref. 16). The nature of the outburst differs among the cataclysmic variables: in novae and recurrent novae, the outburst is associated with unstable nuclear burning of hydrogen-rich material accreted on the surface of the white dwarf, while in dwarf novae, the outburst is associated with a sudden increase in mass transfer from the red dwarf.

Observations during the first two years of operation of the IUE have yielded a great wealth of data concerning cataclysmic variables, including observations of several novae at outburst. Rather than reviewing all these data, I shall use studies of Nova Cyg 1978 and the dwarf nova, Ex Hya, as examples of IUE investigations. Later on in this symposium, we shall be hearing more on cataclysmic variables (Lambert et al. "Old Novae"; Hartmann and Raymond, "Cataclysmic Variables"; Fabbiano et al., "Accreting Degenerate Dwarfs").

Nova Cygni 1978

Nova Cyg 1978 is the first nova for which detailed ultraviolet observations have been obtained, and it is a tribute to the flexibility of IUE operations, that it could start observing this fast nova within a day after it reached (visual) maximum. Figure 3 shows the development of the far-ultraviolet spectrum of Nova Cyg (ref. 17) from its initial absorption-line phase to its nebular phase six months later. Once in the nebular phase, the great strength of the nitrogen lines, NV $\lambda 1240$, NIV] $\lambda 1486$, NIII] $\lambda 1751$, becomes apparent. Seaton (ref. 18) has made a preliminary abundance analysis of the nebula and finds a nitrogen-to-carbon abundance ratio of two, that is, nearly seven times the solar ratio. This enrichment of nitrogen implies that some of the ejected material has undergone hydrogen burning by the CNO cycle, as predicted by the nuclear-runaway theory (ref. 19). Also consistent with the nuclear-runaway theory is the finding of near-constancy of the bolometric luminosity during visual decline (ref. 20).

Ex Hya

Ex Hya is a dwarf nova having a binary period of 99 minutes and an interval between outbursts of about 15 months. It also happens to be a soft x-ray source. Figure 4 shows the flux distribution of Ex Hya during quiescence as obtained by simultaneous IUE and ground-based observations (ref. 21). It is immediately apparent from this figure how crucial IUE observations are in extending spectral coverage of dwarf novae into the region of maximum flux, and hence, in making adequate comparisons with theoretical flux distributions. Bath, Whelan, and Pringle (ref. 21) find that the observed flux distribution of Ex Hya is consistent with that of an optically thick accretion disk. This fit is a fruitful comparison with theory, in that important physical properties may then be derived, including

the rate of mass transfer, $\dot{M} \approx 1 \times 10^{-9} M_{\odot}$ per year, as well as physical and geometrical properties of the disk ($R_{\text{disk}} \approx 50 R_*$, $T_{\text{disk}}(R = 1.36 R_*) = 34800^\circ\text{K}$, $T_{\text{disk}}(r \approx 50 R_*) = 3700^\circ\text{K}$) and the white dwarf ($T_* = 70000^\circ\text{K}$). From a comparison of the soft x-ray flux with the estimated bolametric flux, Bath et al. infer that the x-ray flux is generated in the "boundary layer" where disk material skids to a landing on the stellar surface.

Accretion Onto Magnetic White Dwarfs - AM Her

Earlier I mentioned that there appear to be two types of accreting degenerate dwarfs - the non-magnetic or weakly magnetic stars, to which most of the cataclysmic variables belong, and the highly magnetic degenerate dwarfs, of which AM Her is a spectacular example. In the case of AM Her, the picture of accretion is one in which material flows from the red dwarf onto the magnetosphere of the white dwarf and spirals in to the stellar surface at the magnetic poles. The predicted spectrum of accretion (ref. 22) onto magnetic degenerate dwarfs differs from that of non-magnetic dwarfs in the presence of strong ultraviolet cyclotron radiation associated with strong magnetic fields. Intense UV emission, however, is not observed in AM Her, according to Raymond et al. (ref. 23), a finding which presents a severe difficulty for the theory of polar accretion. Later on in this symposium, we shall be hearing from Dr. Chanmugan more about this discrepancy and possible resolutions.

4. X-RAY BINARIES

In the past two years, an international team of IUE observers has succeeded in observing all known x-ray binaries within the limits of sensitivity of the IUE. The appendix summarizes the IUE data obtained on massive x-ray binaries and low-mass x-ray binaries. The distinction among x-ray binaries according to the mass of the optical primary is also a distinction in source of accreted material: in the massive x-ray binaries, the primary generally loses mass via a high-velocity wind, while in the low-mass binaries, the primary generally loses mass through overflow of its Roche lobe. IUE observations have proved to be essential in clarifying the properties of the wind of the massive x-ray binaries, and they have proved most useful in identifying the component mechanisms of x-ray emission of low-mass x-ray binaries, and hence, in clarifying the process of accretion onto the compact object.

Massive X-Ray Binaries

Perhaps the most outstanding achievement of the IUE observers in studying massive x-ray binaries has been the detection of phase-dependent variations in the profiles of unsaturated wind lines such as the Si IV or C IV resonance doublets. This phase dependence is evident even in low-dispersion spectra of Cyg X-1, SMC X-1 and LMC X-4 (ref. 24), but it shows up most markedly in the high-dispersion spectra of Vela X-1 (ref. 25). Figure 5 shows how the profiles of the Si IV wind lines vary with binary phase. This variation was first predicted by Hatchett and McCray (ref. 26) as a consequence of ionization of the wind in the vicinity of the compact object. McCray's prediction as applied to Vela X-1 is illustrated in Figure 6. In

the vicinity of the x-ray source, material is so highly ionized that there are no ions capable of scattering stellar photons. Hence at $\phi = 0.5$, when the highly ionized cavity lies in front of the primary, the high-velocity shoulder of the absorption component disappears, while the emission component is relatively unaffected. Conversely, at $\phi = 0.0$, when the ionization cavity lies behind the primary, the absorption component is unaffected, but the emission component, arising partly in material receding from the observer, is diminished. This is, indeed, what is actually observed.

5. GLOBULAR CLUSTERS

The IUE has proved useful both in detecting and in locating ultraviolet-emitting sources in globular clusters. So far, six globular clusters, including three known x-ray emitters, have been observed with the IUE (ref. 27). In general, the UV spectra of globulars indicate a mixed stellar content: the near-UV emission arises from late-type horizontal-branch stars and giants, while the far-uv emission usually arises from blue horizontal-branch stars. The ultraviolet properties of blue horizontal-branch stars, both those in clusters and field stars, will be described later on in this symposium by Dr. deBoer.

Dupree et al. (ref. 27) find that in the metal-poor globulars (which are expected to have blue horizontal-branch stars) the ultraviolet surface brightness becomes more centrally concentrated toward shorter wavelengths, a finding which suggests that blue horizontal-branch stars are segregated toward the center. If this concentration is the effect of segregation by mass, it may be an indication that these stars are binary (ref. 28). If so, this would be strong support of the binary origin of x-ray emission in globular clusters.

One of the clusters studied is the metal-rich cluster, NGC 6624, which is also an x-ray burster. The IUE observations indicate a point-source of far-UV emission. Since NGC 6624 is a metal-rich cluster, it is unlikely that this source is a blue horizontal-branch star. Instead, Dupree et al. suggest it may be the x-ray source itself.

6. SUMMARY AND ACKNOWLEDGEMENTS

Although it must be apparent from this review, let me list explicitly some of the ways in which the IUE has proved useful in studying highly-evolved stars. We have seen how important high-dispersion spectra are for abundance analyses of the sdO stars and for studies of the wind from the central star of NGC 6543 and the wind from the O-type component of Vela X-1. We have seen how important low-dispersion spectra are for absolute spectrophotometry of the dwarf nova, Ex Hya. We have seen how important angular resolution is for detecting and locating UV-sources in globular clusters. Finally, we have seen how important operational flexibility is in documenting the behavior of Nova Cyg 1978 at outburst. This is a nice set of features to have on an ultraviolet satellite, features which should assure continued fruitful research on highly-evolved stars in the future.

In closing, I would like to thank all those who sent me reports on their investigations of highly-evolved stars with the IUE. It is on these reports that this review is based.

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APPENDIX

INFORMAL BIBLIOGRAPHY OF STUDIES OF HIGHLY-EVOLVED STARS WITH THE IUE

The following appendix lists reports of IUE observations of highly-evolved stars. Many of these reports were presented either at this symposium or at the IUE Symposium at Tubingen in March, 1980. In the following bibliography, the former papers are referenced as "This Volume," while the latter are referenced as "IUE 2", which is shorthand for "The Second European IUE Conference," which will be published and made available from: Scientific and Technical Publications Branch, ESTEC, Postbus 299, 2200 AG Noordwijk, The Netherlands.

HOT SUBLUMINOUS STARS

SdO Stars

BD +75° 325 }
 HD 49798 }
 HD 127493 }

{ Kudritzki et al. (1980), IUE2
 { Gruschinske et al. (1980), IUE2
 { Simon et al. (1980), IUE2

HD 149382

Baschek, Scholz, and Kudritzki (1980),
 IUE2

HD 205805

Baschek, Scholz, and Kudritzki (1980),
 IUE2

BD +37° 442

Rossi, Viotti, Darius, and D'Antona
 (1980), IUE2

BD +37° 1977

D'Antona, Rossi, and Viotti (1980), IUE2

BD +48° 1777

D'Antona, Rossi, and Viotti (1980), IUE2

Helium - Rich Stars

BD -9° 4395

Heber and Schön["]bern (1980), IUE2

BD +10° 2179

Heber and Schönbern (1980), IUE2

Halo Stars

Feige 86

Hack (1979) A&A 75, L4

Hack (1980) A&A 81, L1

HD 192273

Bromage et al. (1980), IUE2

Hack and Stalio (1980), This Volume.

Central Stars of Planetary Nebulae

NGC 6826

Heap (1979), in Mass Loss and Ev of O Type Stars

Abell 78

— — —

Pottasch and Gauthier (1980), This Volume.

Horizontal - Branch Stars

de Boer (1980), This Volume

WHITE DWARFS

Sirius B	DA	Böhm-Vitense et al. (1979) Ap. J. <u>232</u> , L189
HZ Her	DA	Greenstein and Oke (1979), Ap. J. <u>229</u> , L141
HZ 21	DO	Greenstein and Oke (1979), Ap. J. <u>229</u> , L141
G 186-31	DA	Greenstein and Oke (1979), Ap. J. <u>229</u> , L141
G 261-43	DA	Greenstein and Oke (1979), Ap. J. <u>229</u> , L141
LP 145-141	C ₂	Weidemann et al. (1980) A&A <u>83</u> , L13
WD Companions to BaII Stars		Böhm-Vitense (1980) This Volume

AM Her-LIKE OBJECTS

AM Her		Raymond et al. (1979), Ap. J. <u>230</u> , L95 Tanzi et al. (1980), A&A <u>83</u> , 270 Chanmugan (1980), This Volume Fabbiano, Steiner, et al. (1980), This Volume
AN UMa		Hartman (1980), This Volume
2A0311-227		Hartman (1980), This Volume

CATAclysmic Variables

<u>Novae</u>	Outburst	Reference
Nova Cyg	1978	Sparks, Wu, Holm, and Schiffer (1979), <u>Highlights in Ast.</u> Vol. 5 Casatella et al. (1979), A&A 74, L18 Stickland et al. (1979), Preprint Seaton (1980), IUE2 ("Gaseous Nebulae")
HR Del	1967	Hutchings (1979), PASP 91, 661 Duerbeck et al. (1980), IUE2 Delcina - Hacyan et al. (1980), IUE2 Duerbeck and Seitter (1980), IUE2
RR Pic	1967	Duerbeck et al. (1980), IUE2 Duerbeck and Seitter (1980), IUE2
DQ Her		Hartmann (1980), This Volume
V603 Agl. (old Novae)	1918	Duerbeck et al. (1980), IUE2 Lambert et al. (1980), This Volume
<u>Recurrent Novae</u>		
U Sco	1979	Sparks et al. (1979), in <u>Highlights of Ast.</u> , Vol. 5
WZ Sge	1978	Holm et al. (1979), in <u>Close Binary Systems</u> , (IAU Symp 88) Freidjung et al. (1980), IUE2
T CrB	1946	Duerbeck et al. (1980), IUE2 Duerbeck and Seitter (1980), IUE2
<u>Dwarf Novae</u>		
SS Cygni		Heap et al. (1978), Nature 275, 385 Fabbiano, Steiner et al. (1980), This Volume
RU Peg		Duerbeck and Seitter (1980), IUE2
BV Cen		Bath, Pringle, and Whelan (1980), MNRAS 190, 185.
EX Hya		
VW Hyi		

X-RAY BINARIES (Reviewed by Hammeschlag - Hensberge (1980) IUE2)

Massive X-Ray Binaries

HD 153919	=	1700-37	O6.5f	Dupree et al. (1978), Nature <u>275</u> , 400
HD 77581	=	Vela X-1	B0.5Ib	Dupree et al. (1980), in press (Ap. J., June 1980)
HD 226868	=	Cyg X-1		Treves et al. (1980), in press (Ap. J., June 1980)
				Dupree et al. (1978), Nature <u>275</u> , 400
Sk 160	=	SMC X-1	B0I	Bonnet - Bidaud et al. (1980), in press (A&A)
PH-Sk	=	LMC X-4	O8III	Bonnet - Bidaud et al. (1980), in press (A&A)
X Per	=	0352 +30	O9.5IV-Ve	Hammerschlag - Hensberge et al. (1980), in press (A&A)
He 715	=	1145-61	B1Ve	Hammerschlag - Hensberge et al. (1980), in press (A&A)
LSI +61°303				Hutchings (1979), PASP <u>91</u> , 657
HD 152667	=	1653-46		Hutchings and Dupree (1980), in press (Ap. J.)

Low-Mass Binaries

- V 818 Sco = Sco X-1 Willis et al. (1980), in press (Ap. J., June 1980)
- V 1341 Cyg = Cyg X-2 Maraschi et al. (1980), preprint
- HZ Her = Her X-1 A-F Gursky et al. (1980), in press (Ap. J., June 1980)
- Dupree et al. (1978), Nature 275, 400
- AM Her = 1814 +49 Mag WD Raymond et al. (1979), Ap. J. 230, L95
- Tanzi et al. (1980), A&A 83, 270
- Chanmugan (1980), This Volume.

PULSARS-SN

- Crab Pulsar Benvenuti et al. (1980), This Volume
- SN1979 in M100 Panagia (1980), This Volume

GLOBULAR CLUSTERS

- M 15 x-ray
- NGC 1851 x-ray
- NGC 6624 x-ray, metal-rich
- 47 Tuc metal-rich
- M92
- NGC 6752
- Dupree et al. (1979), Ap. J. 230, L89
- Hartman (1980), in press, ("Galactic X-Ray Sources", J. Wiley, 1980)

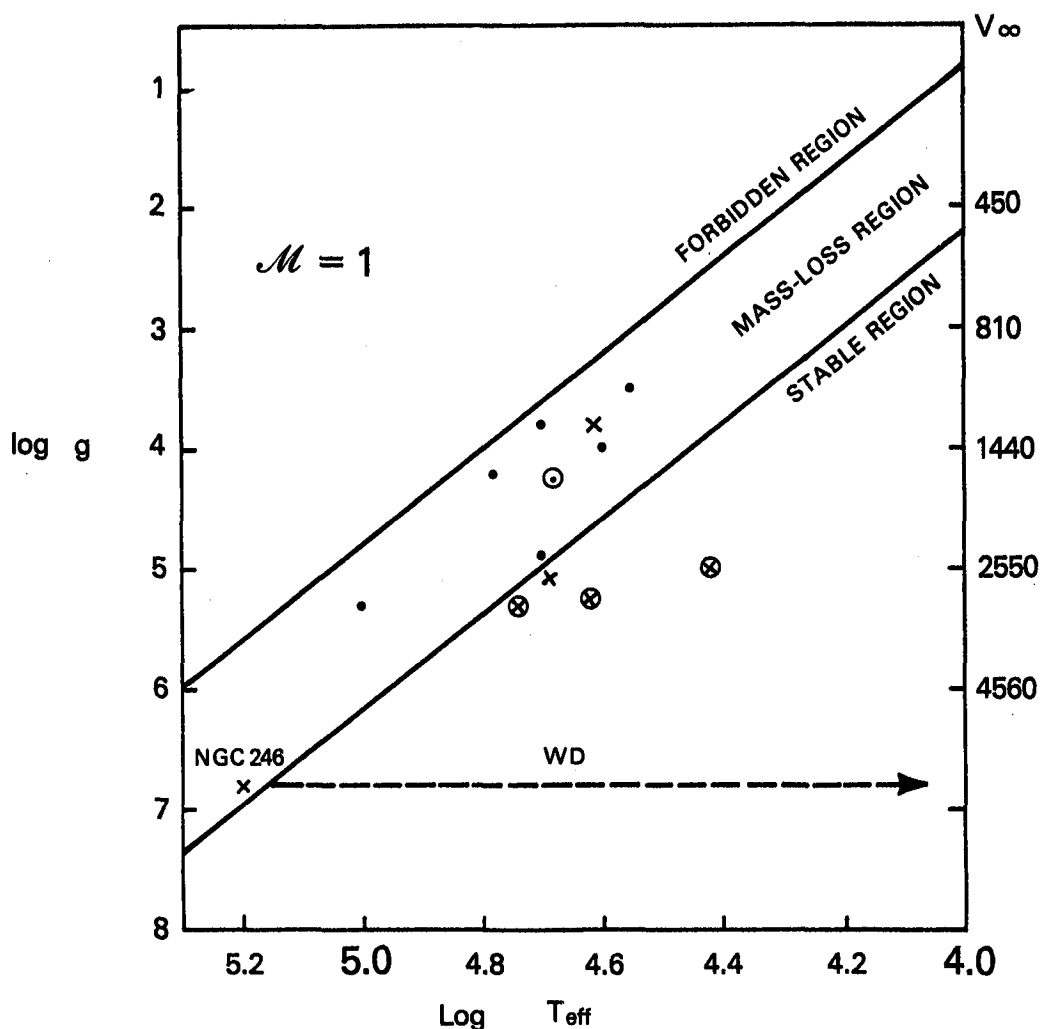


Figure 1. Temperature-Gravity Diagram for Hot, Subluminous Stars Observed with the IUE. The right-hand ordinate is the terminal velocity of the wind predicted for a one-solar-mass star. Stars whose UV-spectra show P Cygni profiles indicating a high velocity wind are denoted by dots, while those showing no evidence for a wind are denoted by crosses. Those stars for which the atmospheric parameters have been estimated by a full non-LTE analysis (ref. 3-6) are denoted by circles. The boundary line to the forbidden region is the Eddington limit for a one solar-mass star. The boundary line to the stable region is an extrapolation of the boundary found for young OB stars (ref. 8).

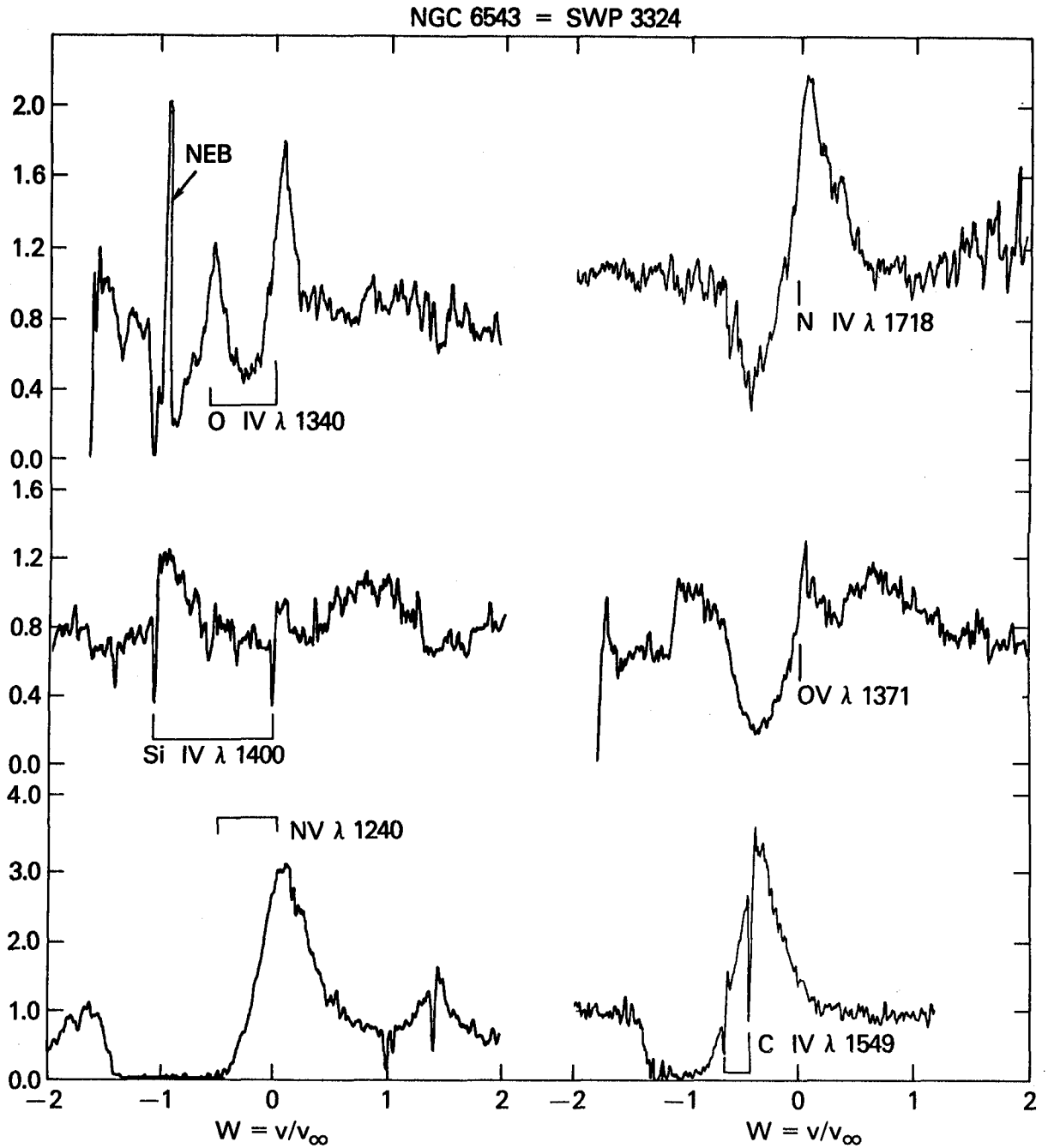


Figure 2. Wind Profiles in the Spectrum of the Central Star of NGC 6543. The image from which these normalized profiles were derived has been reprocessed to correct for earlier ITF errors.

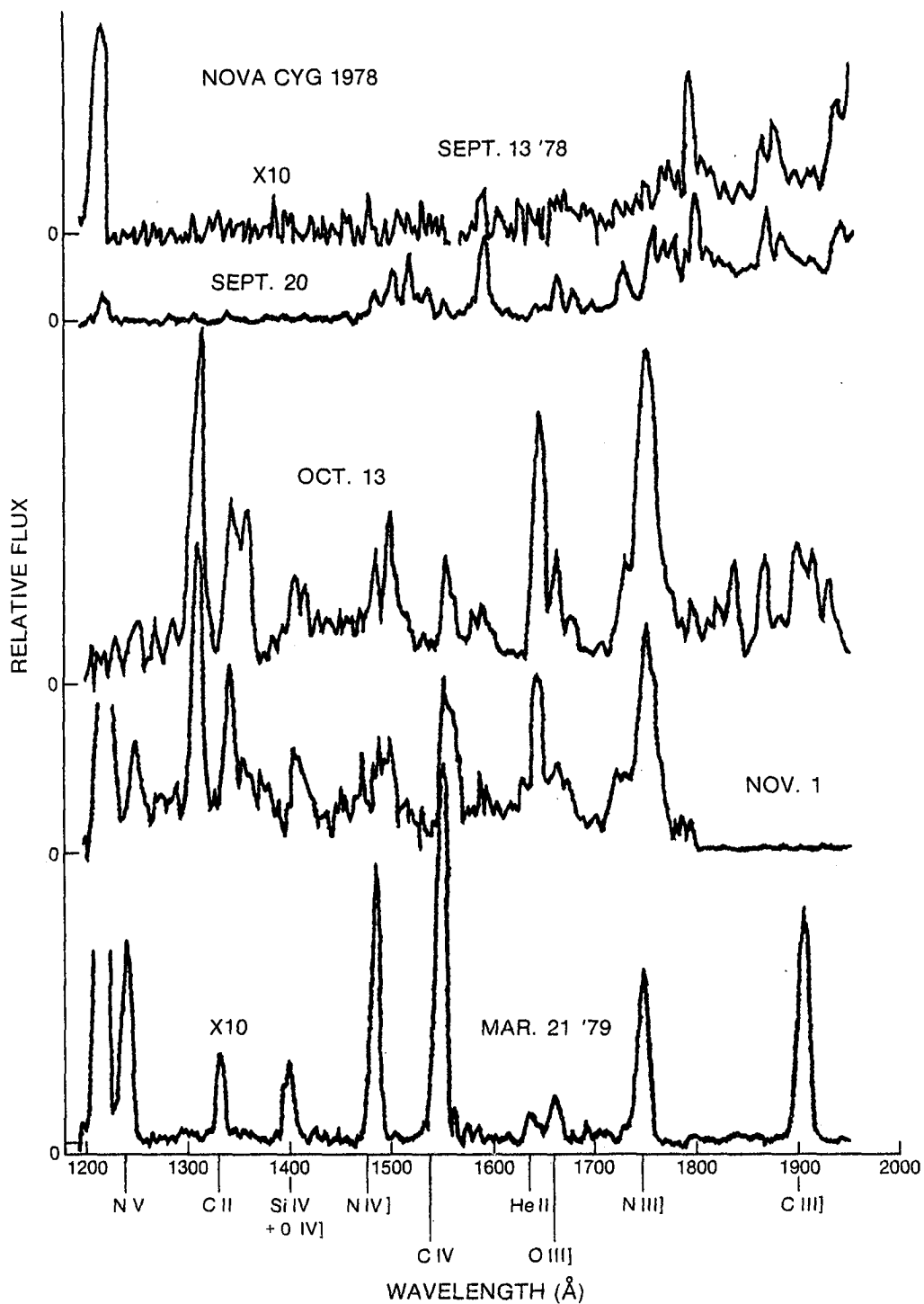


Figure 3. Development of the Far-UV Spectrum of Nova Cyg 1978 (reproduced from ref. 17).

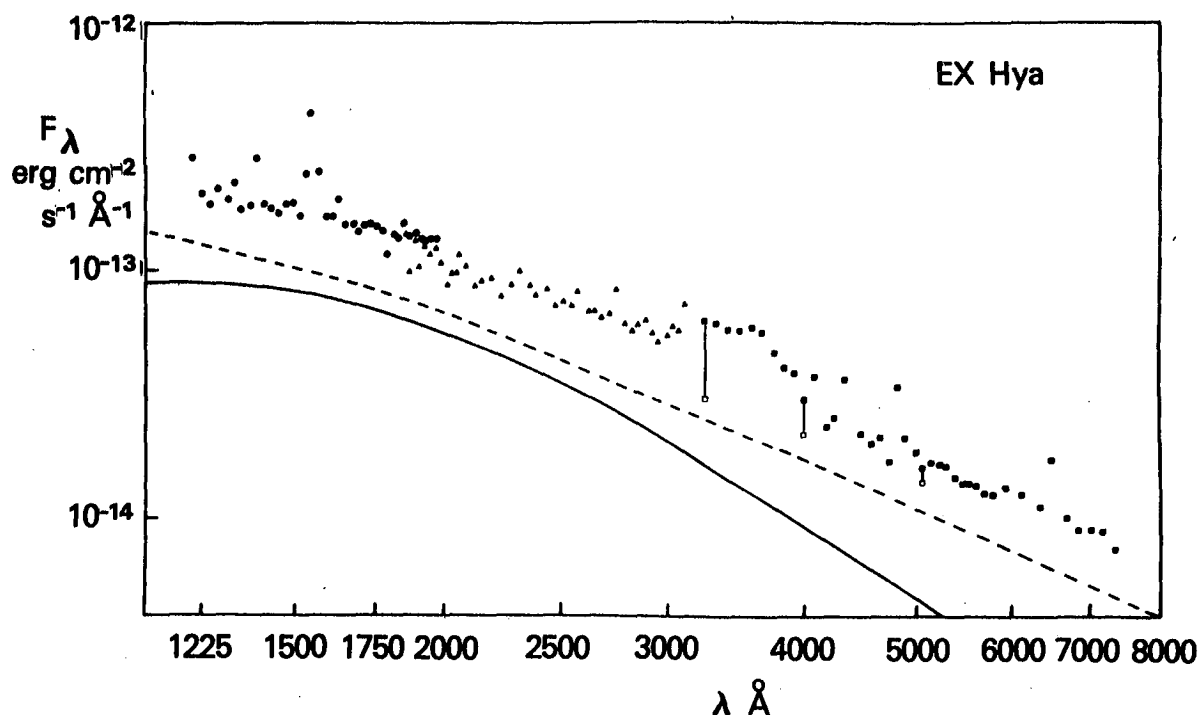


FIG. 4 THE SPECTRUM OF EX Hya OBSERVED IN QUIESCENCE. THE CIRCLES ARE SHORTWAVE, AND THE TRIANGLES LONGWAVE, OBSERVATIONS WITH IUE. THE FILLED SQUARES ARE AAT OBSERVATIONS CORRECTED FOR ATMOSPHERIC EXTINCTION. THE MAGNITUDE OF THE CORRECTION IS INDICATED BY THE OPEN SQUARES. THE SOLID LINE IS THE BEST FIT BLACK BODY TO THE ULTRAVIOLET DATA CORRESPONDING TO $T = 24\,000\text{K}$. THE DASHED LINE IS THE BEST FIT ACCRETION DISC SPECTRUM DISCUSSED IN THE TEXT. BOTH THESE LINES HAVE BEEN DISPLACED DOWNWARDS SO THAT THEY DO NOT INTERFERE WITH THE DATA POINTS.

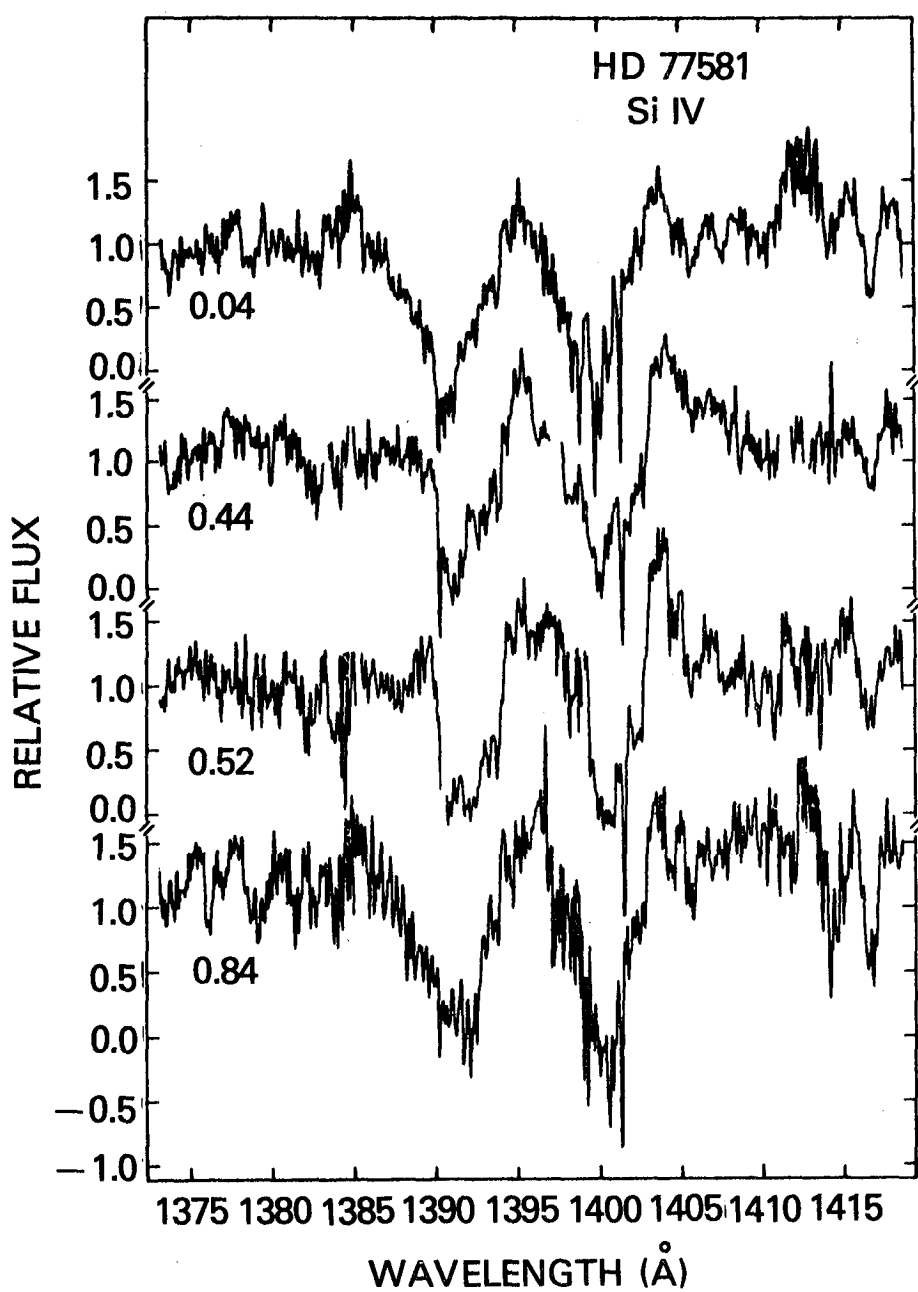


Figure 5. Si IV lines as a function of phase from high dispersion spectra. Note the substantial changes in the blue wing of both lines, and the appearance of a high velocity absorption feature at phase 0.52 (reproduced from ref. 25).

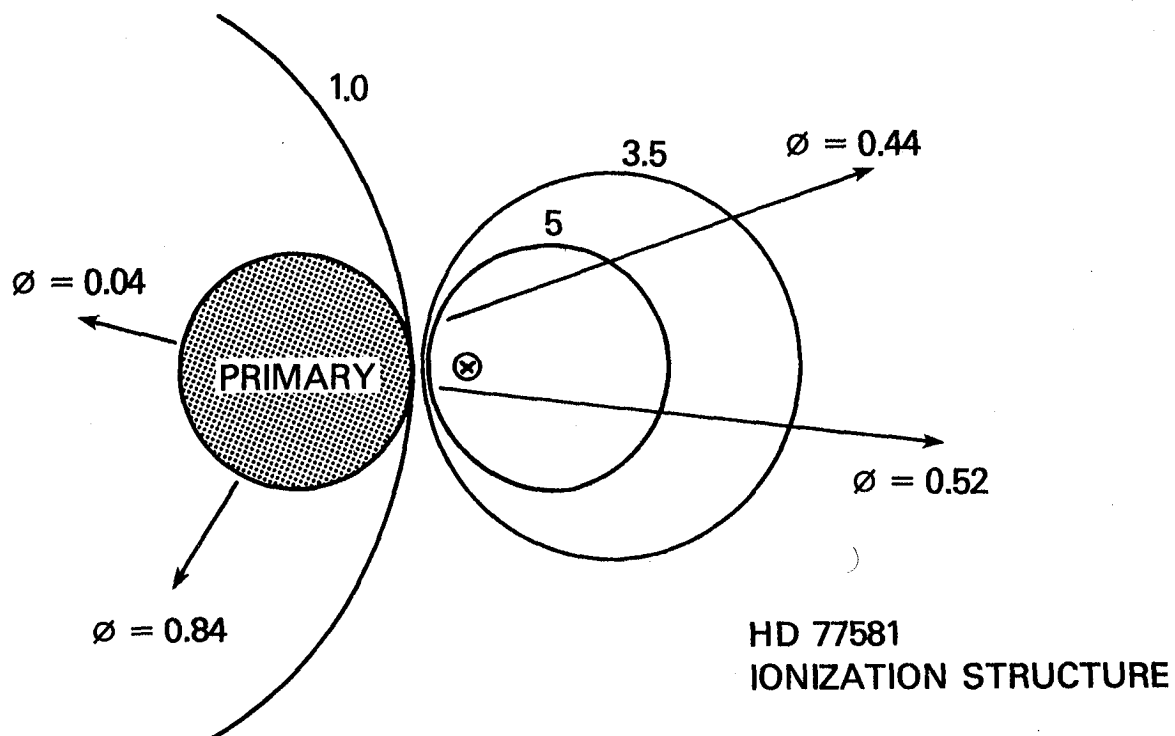


Figure 6. Predicted ionization surfaces for $q = 3.5$ and $q = 5$; within these spheres, it is assumed that an ion is missing from the volume to the right of the $q = 1$ locus (reproduced from ref. 25).